State feedback control model can account for differences in abnormal pitch perturbation responses in Alzheimer's disease and cerebellar ataxia

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Introduction: The computational and neural mechanisms underlying abnormal speech motor control remain poorly understood for a variety of neurological disorders. We have previously reported abnormal responses to pitch perturbations in Alzheimer's disease (AD) and cerebellar ataxia (CA). Here, we attempted to account for these abnormalities using a computational model of speech motor control. Specifically, we simulated the behavioral response to pitch perturbations, and examined how model behavior varied as a function of parameters.

Our model of speech motor control is based on principles of state-feedback control (SFC) [1]. In this model, motor commands are generated based on an internal estimate of vocal tract state. The estimated state and the generated commands are used to predict vocal tract state and auditory and somatosensory feedback for the next time step. The predictions are then compared with the actual feedback to calculate error signals. These errors are scaled by a Kalman gain and used to update the predicted state of the vocal tract, which is used to generate the next set of commands.

In the SFC model, the time course of response to pitch feedback perturbation is determined by model parameters like Kalman gains on auditory and somatosensory prediction errors, which in turn depend on the amplitude of sensory feedback noise and duration of feedback delays. By exploring parameter settings that best match features of the simulated time course of output pitch to experimental data in patients and controls, we can generate hypotheses about how the speech motor control system may function differently in the disorders.

Results: Our previously developed SFC model [1] was used to simulate the behavioral pitch output response to a 400 ms pitch perturbation of 100 cents. Results were first compared to the published experimental data shown in Figure 1A, in which the behavioral responses of control subjects are compared to those of Alzheimer's disease (AD) patients [2]. A simulated response matching features of the controls data set was used as a starting point, with a peak value of about 20 cents different from baseline and vertical asymmetry due to a slower fall in pitch back toward baseline than rise toward peak compensation. We found that if the Kalman gains on both auditory and somatosensory feedback prediction errors were scaled by the same factor, the simulated response matched many of the features of the AD patient data set, with a slightly higher peak, a greater initial slope, and a faster return toward baseline pitch (Figure 1B).

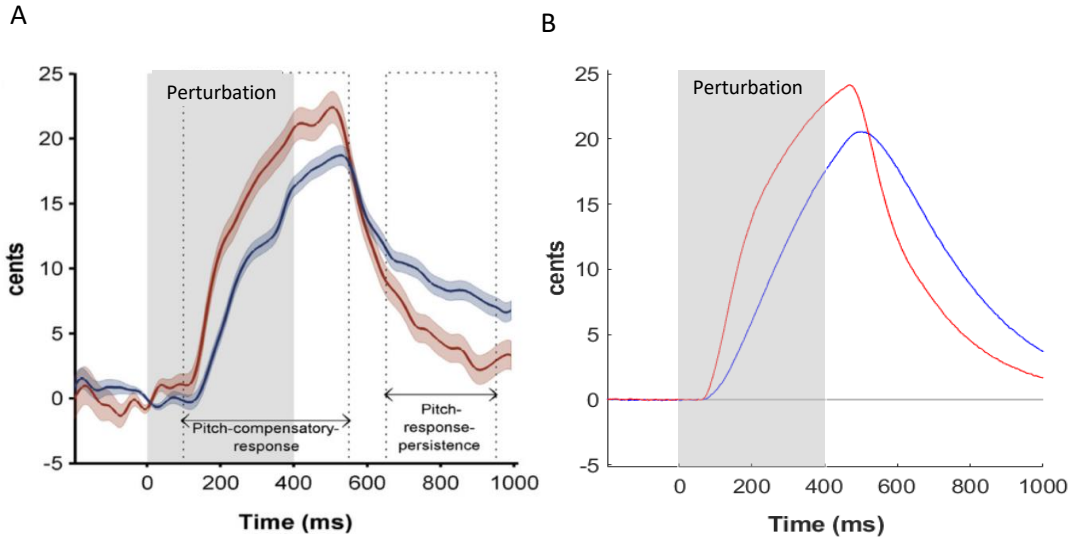

Figure 1: Scaling Kalman gain on auditory and somatosensory feedback in simulation (B) can reproduce many of the differences observed experimentally [2] (A) between the pitch perturbation responses of controls (blue) and AD patients (red).

Similarly, model results were compared to the published pitch perturbation responses of controls and cerebellar ataxia (CA) patients shown in Figure 2A [3]. A simulated response that matched features of the control data set was used as a starting point, with a peak compensation value of about 20 cents, a sudden decrease in slope about 200 ms after the start of the perturbation, a sharp turn toward baseline pitch immediately after reaching peak compensation, and a gradual flattening of slope as the pitch falls toward baseline. It was found that increasing the amplitude of somatosensory noise relative to auditory noise (which attenuated Kalman gain on somatosensory feedback prediction errors) produced a simulated response that matched many features of the CA patient data set, with a larger peak response, a steeper secondary rise in response, and a return towards baseline response that did not surpass that of the control data set (Figure 2B).

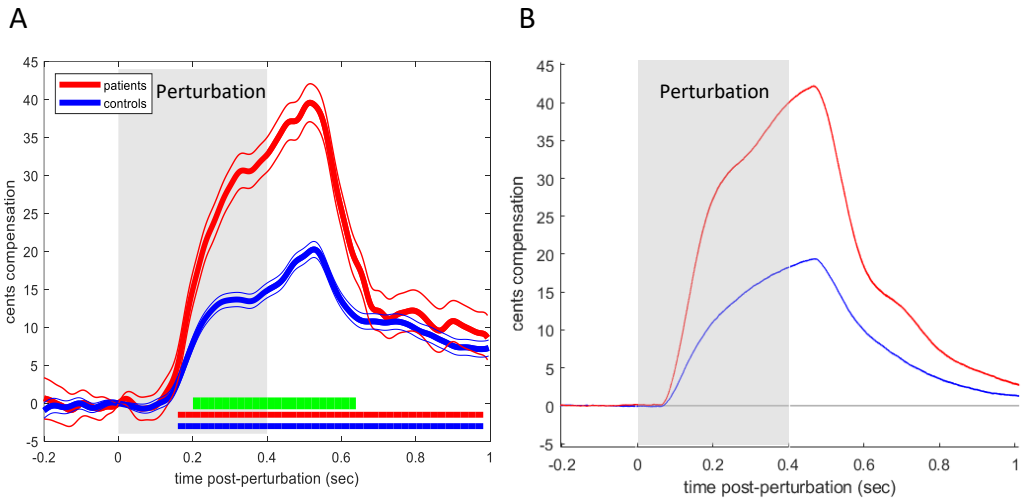

Figure 2: Scaling somatosensory noise in simulation (B) can reproduce many differences observed experimentally [3] (A) between the pitch perturbation responses of controls (blue) and CA patients (red).

Discussion: No quantitatively verifiable model of the vocal tract exists due to the heterogeneity of vocal tract dimensions, damping, and other properties across individuals. This prevents a quantitative comparison between simulated model outputs and experimental results of pitch perturbation studies. However, a qualitative analysis of modelling results can provide insights into which computational and neural mechanisms may differ between patient and control populations, and lead to testable hypotheses for behavioral imaging studies.

In simulation, a uniform scaling of Kalman gains on both auditory and somatosensory feedback can reproduce many of the differences observed between AD patients and controls. This leads to the hypothesis that higher overall Kalman gains are found in AD patients than in controls, but AD patients and controls have similar ratios of gains on auditory and somatosensory feedback.

On the other hand, differences between CA patients and controls were best modeled by selectively scaling somatosensory noise and Kalman gain on somatosensory prediction errors. This leads to the hypothesis that CA patients have greater Kalman gain for auditory feedback prediction error than somatosensory feedback prediction error. This could either be due to greater somatosensory noise, or to lower auditory noise in CA patients compared to controls.

A goal of future simulations is to more accurately model response persistence, i.e. the return to baseline pitch after perturbation offset and how it varies between controls and patient groups. Experimentally, the effect of a 400 ms pitch perturbation persists such that even 600 ms after perturbation offset, the subjects' pitch remains 4-10 cents above pre-perturbation baseline.

Conclusions: We have demonstrated that our SFC model can replicate key ways in which the pitch perturbation response of AD and CA patients differ from controls, through simulated changes in Kalman gain and relative noise scaling. These findings lead to distinct testable hypotheses about how the computational and neural mechanisms of speech motor control in AD and CA patients differ from controls. This overall approach can lead to greater understanding of the neural processes of speech motor control and how these processes are affected in neurodegenerative diseases.

Citations: [1] Houde et al. (2014) *10th ISSP.* 202-205. [2] Ranasinghe et al. (2017) *Neurobiol. Aging.* 52:71-80. [3] Houde et al. (2019) *J. Acoust. Soc. Am.* 145(5): EL372.